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AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
Inglewood, California

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AN EXPERIMENTAL STUDY OF THE PARALLEL PUMPED FERROMAGNETIC AMPLIFIER*

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*Based on work performed at Hughes Aircraft Co., Culver City, Calif.

ABSTRACT

The performance characteristics of the parallel pumped magnetostatic amplifier are experimentally determined. The gain bandwidth product and noise figure are measured as a function of pump power and compared with the usual parametric amplifier theory. Deviations occur which originate from a broadening of the signal and idle magnetostatic modes. This linewidth broadening increases with pump power and is due to pump saturation effects. When the usual theory for the gain bandwidth and noise figure is corrected, close agreement is obtained with the experimental data.

CONTENTS

Introduction

Suhl[1] first analyzed the operation of the ferromagnetic amplifier and demonstrated, for a perpendicular pumping field, that magnetostatic modes can be parametrically excited by a nonlinear coupling to the pump field. This theory has been verified for the electromagnetic, semistatic and modified semistatic types of operation.[2,3] Magnetostatic operation was not obtained until R. T. Denton discovered[4] that magnetostatic modes could be pumped with a field parallel to H_{dc}. Denton developed the theory for the parallel pumped magnetostatic amplifier and verified the basic theory nicely with the measured performance of some amplifier designs.

Characteristic of Denton's amplifiers was a rather high noise figure (about 13 db) which appeared to arise from sample heating (due to spin wave excitation) and spin wave radiation effects. By minimizing sample heating we have been able to measure with some precision the variation of gain-bandwidth product ($\overline{GB}$) and noise figure (F) with pump power. The measured response does not agree with the theoretical variation. However, by including a correction arising from the excitation of spin waves it has been possible to largely account for the experimental results.

Amplifier Theory

It is convenient to briefly set down the equations giving $\overline{GB}$ and F for any parametric amplifier of the type corresponding to Fig. 1.[5,6] Results are expressed in terms of circuit resonant frequencies and Q's, defined by $Q = f \gamma \Delta H$ where ΔH is the mode linewidth, γ the gyromagnetic ratio, and f the resonant frequency. In addition, the coupling to the signal circuit is given by the external or window Q, Q_w. Unless otherwise noted, excitation of only the 311, $3\bar{1}1$ modes (in the notation of Fletcher, et al.[7]) is considered.

The nonlinear pump coupling can be expressed as an effective negative Q, Q_-, in terms of the pump power, P, the minimum pump power required for mode oscillation, P_c, and the signal mode Q, Q_s. If idle and signal mode Q's are equal, which conforms to the usual experimental case,

$$Q_- = Q_s \frac{P_c}{P} \tag{1}$$

The voltage gain for the circuit in Fig. 1 is

$$\sqrt{G} = Q_L \left[\frac{1}{Q_s} - \frac{1}{Q_w} - \frac{1}{Q_-}\right] \tag{2}$$

where $\frac{1}{Q_L} = \frac{1}{Q_s} + \frac{1}{Q_w} - \frac{1}{Q_-}$ defines the loaded Q.

The gain expression can be written as

$$\sqrt{G} = \frac{2Q_L}{Q_s}\left[\frac{\sqrt{G}}{\sqrt{G} - 1}\right]\left[\frac{P}{P_c} - 1\right] \tag{3}$$

The gain bandwidth expression then becomes:

$$GB = \frac{2f_s}{Q_s}\left[\frac{\sqrt{G}}{\sqrt{G} - 1}\right]\left[\frac{P}{P_c} - 1\right] \tag{4}$$

The noise figure, F, can be derived for the circuit of Fig. 1 and, assuming equal temperature for all circuit components,

$$F = \frac{N_o}{G N_i} = 1 + \frac{4 Q_L^2}{Q_s Q_w G} + \frac{4 Q_L^2 f_s}{Q_- Q_w G f_i} \quad . \tag{5}$$

It is convenient to rewrite the expression in the form

$$F = 1 + \left(\frac{\sqrt{G} + 1}{\sqrt{G}}\right)^2 \frac{Q_w}{Q_s} \left(1 + \frac{f_s}{f_i}\right) + \frac{G - 1}{G} \frac{f_s}{f_i} \quad . \tag{6}$$

Notice that for high gain and for $f_s \approx f_i$ he smallest value of F attainable is $F = 2$ which corresponds to the heavily coupled case where $Q_w = 0$. A substitution for Q_w can be made in terms of the pump power, an easily measured quantity. Utilizing equation 1 the noise figure expression then becomes

$$F = 1 + \frac{G - 1}{G} \left\{ \frac{\frac{P}{P_c} \frac{f_s}{f_i} - 1}{\frac{P}{P_c} - 1} \right\} \quad . \tag{7}$$

The above expressions are based on the assumption that there are no pump saturation effects so that $-1/Q_-$ (the negative resistance introduced by the pump) is proportional to the pump power. When saturation effects take place, the above theory must be modified as will be shown later.

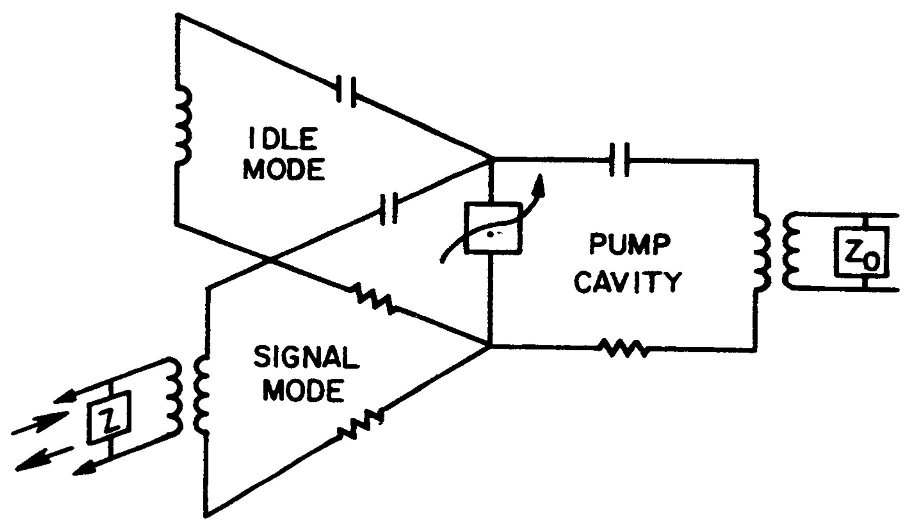


Figure 1 - Equivalent Circuit of a Cavity Type Parametric Amplifier

Experimental Results

Measurements were made on a magnetostatic amplifier constructed similar to Denton's design. The pump cavity utilized the TE_{101} mode resonant at 9,236 MC and contained the YIG sphere mounted at the back wall. The sphere was 0.40 inch in diameter and exhibited a main resonance linewidth of 0.45 oe. A boron nitride cylinder was constructed to hold the sphere to prevent sphere heating at high pump power levels. By sifting boron nitride powder around the sphere good thermal contact was insured and the sphere was free to align itself along the easy [111] direction upon application of H_{dc}. The sphere temperature, estimated from magnetostatic mode frequency shifts, did not exceed 40°C with 3 watts of incident pump power. (To verify the absence of thermal effects, data presented in this section was also taken using pulsed pump power; exact agreement with CW data was obtained.) Using these modes the signal and idle frequencies were 4.648 and 4.588 KMC, respectively. Signal coupling was provided by closely girding the sphere with a loop of wire fed from a transmission line. A double stub tuner was used to alter the coupling and a circulator separated the incident signal and reflected amplified signal.

From equation 4 the variation of $\overline{GB}$ with P for constant gain should be linear as shown in Fig. 2 ($\alpha = 0, \beta = 0$). The experimental points, also shown in Fig. 2, were taken by measuring the bandwidth as a function of pump power, while increasing the coupling to the signal circuit to maintain a constant 14 db gain. A large deviation from the theoretical curve is found and, indeed, the $\overline{GB}$ seems to be limited by a parasitic process.

In like fashion the noise figure also deviated from the simple nonsaturation theory. Figure 3 ($\alpha = 0, \beta = 0$) shows the theoretical variation of F with pump power and shows the experimental results, again for 14 db gain. The measured noise figure slopes away from the theoretical curve toward higher values and attains a minimum of only 10.5 db. The estimated inaccuracy in measuring F is less than ± 0.5 db and the results in Fig. 4 could be repeated consistently to this accuracy. The standard noise tube and calibrated i.f. attenuator method (but with a narrow band i.f. amplifier) were used to make the measurements.

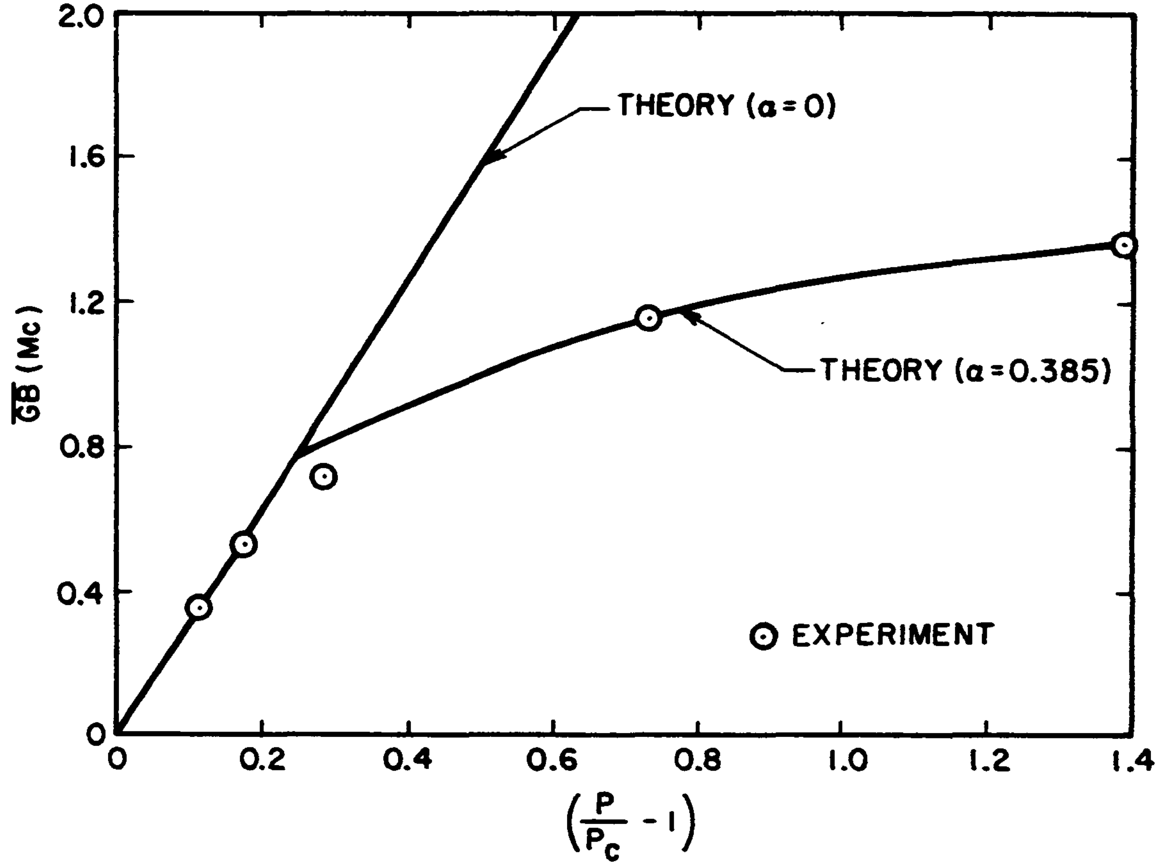


Figure 2 - Gain-Bandwidth as a Function of Pump Power at Constant Gain (14db)

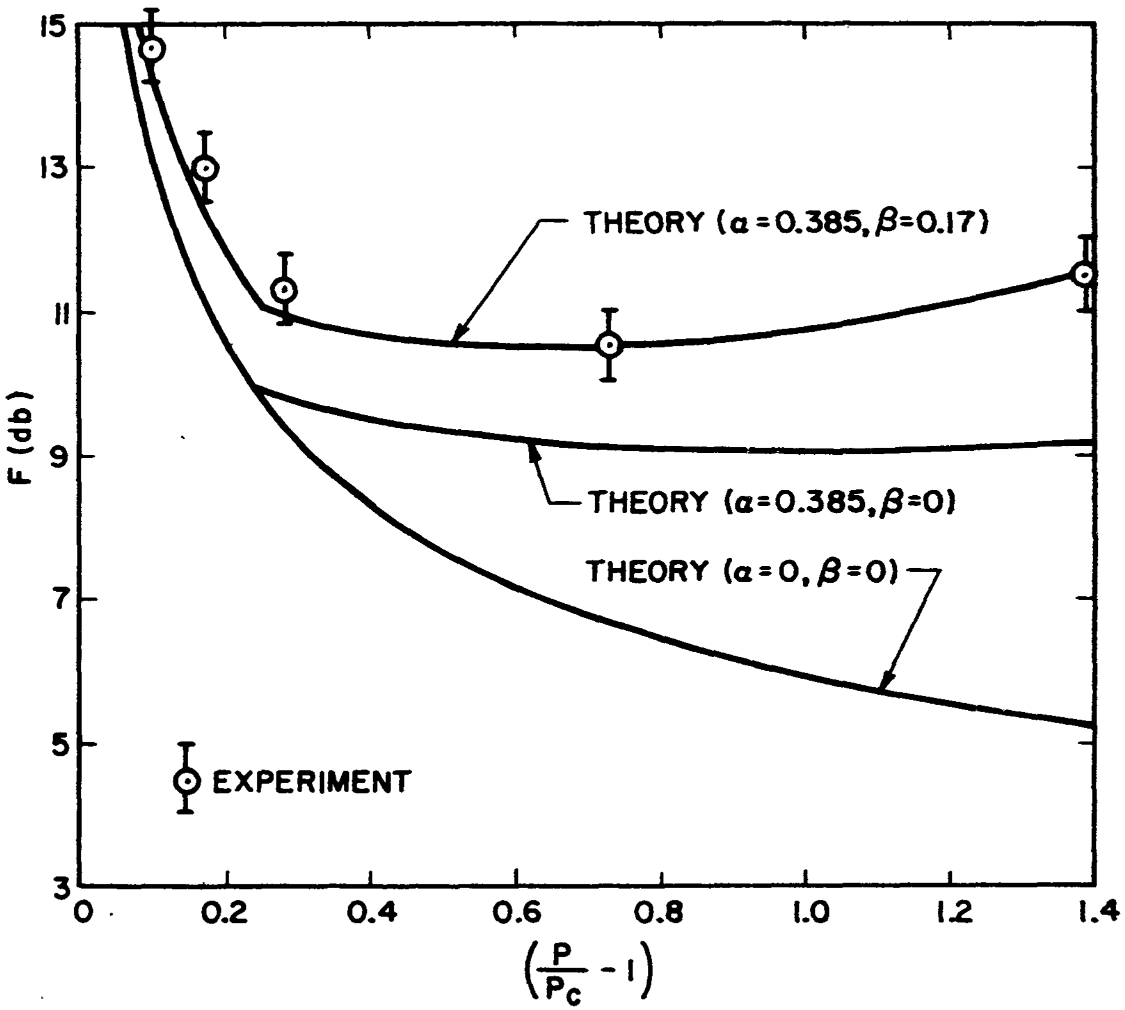


Figure 3 - Noise Figure as a Function of Pump Power at Constant Gain (14db)

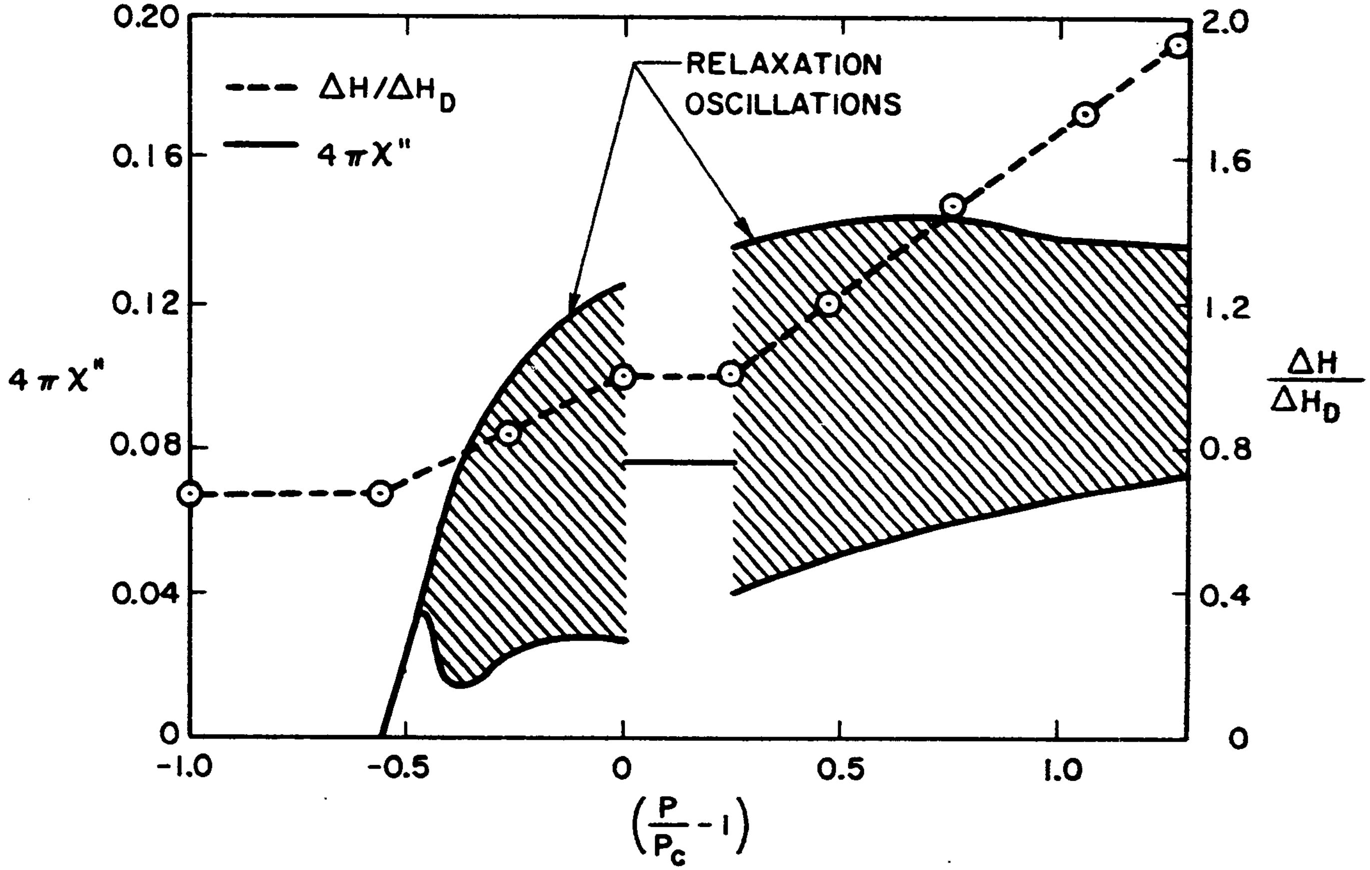


Figure 4 - Signal Mode Linewidth and Pump Subsidiary Absorption as a Function of Power (H_{dc} = 1592oe)

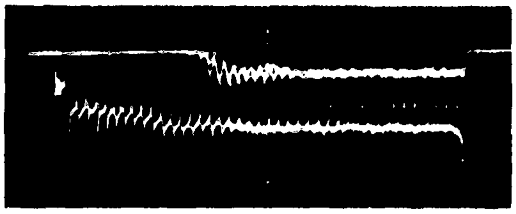
The deviation from theory can be accounted for on the basis of observed pump saturation effects. χ'' at subsidiary resonance has been measured[8] for YIG and is shown in Fig. 4 at the value of H_{dc} required for amplifier operation. Large amplitude relaxation oscillations are observed[8] for certain power regions and the operation of the amplifier is found to be strongly dependent on the variation of χ''. First, the minimum pump power required for mode oscillations, P_c, exactly corresponds to the power level at which the relaxation oscillations cease. Second, the gain-bandwidth product does not disagree with theory until a power level, P_D, is reached which is precisely the value at which relaxation oscillations again become prominent and the average value of χ'' rises. A large deviation in noise figure is also noticed at this power level. It should be noted that the variation of χ'' with pump power is not appreciably affected by magnetostatic mode oscillations, i. e., mode oscillations do not affect the variation of χ'', but rather the converse is true. Pulsed power ($\tau > 50$ μsec) was also applied to the system in order to observe the transient effects at these critical power levels. In Fig. 5 the signal output and reflected pump pulse are shown just below P_c and again just above P_c. The mode oscillations grow as the relaxation oscillations decay, demonstrating the pronounced effect of subsidiary resonance on the amplifier performance.

These observations can be correlated in the following way. With H_{dc} slightly detuned so that mode oscillations would not occur, the linewidth of the signal (311) mode was measured as a function of pump power with the results shown in Fig. 4. In the range where relaxation oscillations occur, ΔH increases linearly with power. From P_c to P_D, where no relaxation oscillations are observed, the linewidth is constant. Based on these measurements a linear dependence of ΔH on power of the form

$$\Delta H = \Delta H_D \left[1 + \alpha \left(\frac{P}{P_D} - 1 \right) \right] \qquad 8)$$

must be injected into equations 4 and 7 to correct the theoretical curves of Fig. 2 and Fig. 3.

(a) $P < P_c$



(b) $P > P_c$

Figure 5 - Signal Output and Reflected Pump Power
Showing Mode Oscillation Buildup
as Relaxation Oscillations Decay

The expressions for $\overline{GB}$ and F then become for $P > P_D$,

$$\overline{GB} = \frac{2 f_s}{Q_s}\left[\frac{\sqrt{G}}{\sqrt{G}-1}\right]\left\{\frac{P}{P_c\left[1+\alpha\left(\frac{P}{P_D}-1\right)\right]}-1-\alpha\left(\frac{P}{P_D}-1\right)\right\} \tag{9}$$

$$F = 1 + \frac{G-1}{G}\left\{\frac{\left(1+\frac{f_s}{f_i}\frac{P}{P_c}\left[1+\alpha\left(\frac{P}{P_D}-1\right)\right]\right)^2}{\frac{P}{P_c}\left[1+\alpha\left(\frac{P}{P_D}-1\right)\right]^2-1}\right\} \tag{10}$$

where Q_s now refers to the mode Q at P_c, and a constant temperature is still assumed for all circuit elements. Equation 9 fits the experimental gain bandwidth results if α is chosen equal to 0. 385. Fig. 2 shows the agreement. Similarly, the variation of F with $[P/P_c - 1]$ is computed using equation 10 with α equal to 0. 385. The corrected theoretical curve is plotted in Fig. 3. Exact agreement with the experimental curve is not found, but the large excursion is accounted for, the general shape is satisfactory, and it is plausible that a small spin wave radiation correction could bring closer agreement.

The value of α obtained from Fig. 4 is α = 1. 14, differing from the value of 0. 385 which fits the experimental gain bandwidth curve. This is not surprising since the data of Fig. 4 was necessarily taken with the 311, $3\bar{1}1$ modes uncoupled. Hence, the reliable $\overline{GB}$ curve is used to determine α. Thus, when the effect of mode broadening is taken into account, a much smaller deviation in F is found. If one assumes an additional effective temperature, T_{eff} which is dependent to first order on the power absorbed at subsidiary resonance, as

$$T_{eff} = T_o\left(1+\beta\left[\frac{P}{P_c^s}-1\right]\right)$$

where T_o is room temperature, and P_c^s is the power for spin wave instability, then the experimental points are brought into agreement for β = 0. 17. Our experiments show that spin waves at a frequency $f_{p/2}$ radiate into the external circuit with a signal strength of the order of microwatts. If $f_{p/2}$ spin waves excite spin waves of frequency f_s and f_i which in turn radiate, then a temperature correction of the form given is not unreasonable. More accurate and complete data are needed to verify this tentative T_{eff} correction.

Discussion

The mode broadening effect due to subsidiary resonance accounts for a major part of the amplifier behavior. The dependence of ΔH on pump power creates a power dependent oscillation threshold, and if severe enough could prevent operation of the amplifier. The rate at which ΔH increases with power in this amplifier prohibits operation for $P < P_c$. If this rate were maintained, regardless of power level, amplification would have been prevented. However, the plateau region occurs in χ'', ΔH remains constant, and amplification is attained.

There are at least two reasonable mechanisms which could cause the linewidth to broaden. First, the z component of the magnetic field associated with the relaxation oscillations can act as a modulation field which increases the signal and idle linewidths in much the same way as has been described[9, 10] for spin waves. The tell-tale sidebands which occur at about one megacycle (the frequency range of the oscillations) on either side of the signal during amplification[4] confirm the occurrence of this source of broadening. This effect cannot be the only cause of mode broadening since the linewidth at P_c does not assume the low power value when the relaxation oscillations cease. A second possible source of broadening arises from the presence of spin waves in the sample. Since their time and spatial dependence both differ from that of the 311 and $3\bar{1}1$ modes, it is speculated that the effect on the mode linewidths for strongly excited spin waves is equivalent to an increase in temperature. The modes will not experience a completely random energy transfer as in the case of heating and one might expect a lineshape distortion to accompany the broadening. Such distortions have been observed. The mode broadening contributed by this effect would be expected to be dependent on the average power absorbed at subsidiary resonance. A suitable combination of the effects may be required to give a reasonable accounting of the mode broadening and thus a quantitative explanation of the amplifier performance.

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